Reaction mechanisms for weakly-bound, stable nuclei and unstable, halo nuclei on medium-mass targets

C. Beck[a], N. Rowley[a*], P. Papka[a†] S. Courtin[a], M. Rousseau[a], F.A. Souza[b], N. Carlin[b], R. Liguori Neto[b], M.M. de Moura[b], M.G. Del Santo[b], A.A.P. Suaide[b] M.G. Munhoz[b], E.M. Szanto[b], A. Szanto de Toledo[b], N. Keeley[c], A. Diaz-Torres[d], K. Hagino[e].

[a]Institut Pluridisciplinaire Hubert Curien, UMR 7178, CNRS-IN2P3 and Université de Strasbourg, B.P. 28, F-67037 Strasbourg Cedex 2, France

[b]Departamento de Fisica Nuclear, Universidade de São Paulo, SP, Brazil

[c]The Andrzej Soltan Institute for Nuclear Studies, Warsaw, Poland

[d]Department of Physics, University of Surrey, Guildford, UK

[e]Department of Physics, Tohoku University, Sendai, Japan

An experimental overview of reactions induced by the stable, but weakly-bound nuclei ^{6}Li, ^{7}Li and ^{9}Be, and by the exotic, halo nuclei ^{6}He, ^{8}B, ^{11}Be and ^{17}F on medium-mass targets, such as ^{58}Ni, ^{59}Co or ^{64}Zn, is presented. Existing data on elastic scattering, total reaction cross sections, fusion processes, breakup and transfer channels are discussed in the framework of a CDCC approach taking into account the breakup degree of freedom.

1. INTRODUCTION

In reactions induced by stable, but weakly-bound nuclei and by exotic (unstable), halo nuclei, the influence on the fusion process of coupling to both collective degrees of freedom and transfer/breakup channels is a key point in understanding the dynamics of many-body quantum systems [1]. Due to their very weak binding energies, the "halo" (a diffuse cloud of neutrons for ^{6}He or an extended spatial distribution for the loosely-bound proton in ^{8}B) will lead to larger total reaction (and fusion) cross sections at sub-barrier energies when compared with predictions of one-dimensional barrier penetration models [1,2]. This enhancement is well understood in terms of the dynamical processes arising from strong couplings to collective inelastic excitations (such as soft-dipole resonances) of the target and projectile. However, in the case of reactions where at least one of the colliding nuclei has a sufficiently-low binding energy for breakup to become a competitive process, conflicting conclusions have been reported [1,2,3,4]. Recent studies with radioactive ion beams (RIB) indicate that the halo nature of ^{6}He, for instance, does not enhance the fusion probability as much as anticipated. Instead, the prominent role of one- and two-neutron

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*Institut de Physique Nucléaire, and Université de Paris Sud, F-91406 Orsay Cedex, France
†Department of Physics, University of Stellenbosch, Marieland, Stellenbosch 7602, South Africa

transfers in ^{6}He-induced fusion reactions [3,5,6,7,8] has been definitively demonstrated. On the other hand, the effect of non-conventional transfer or stripping processes (see e.g. [1]) appears to be less significant for stable, weakly-bound projectiles.

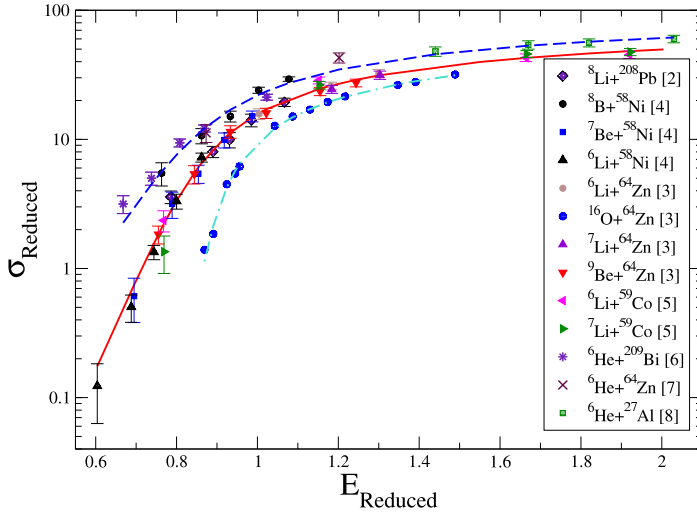## 2. EXPERIMENTAL OVERVIEW

Figure 1. (Color online) Reduced total reaction cross sections for a number of systems taken from the literature [2,4,9,10,11,12,13]. "Reduced" Energies and "reduced" cross sections were extracted following procedures proposed in Refs. [2,12]. The figure was adapted from Ref.[14].
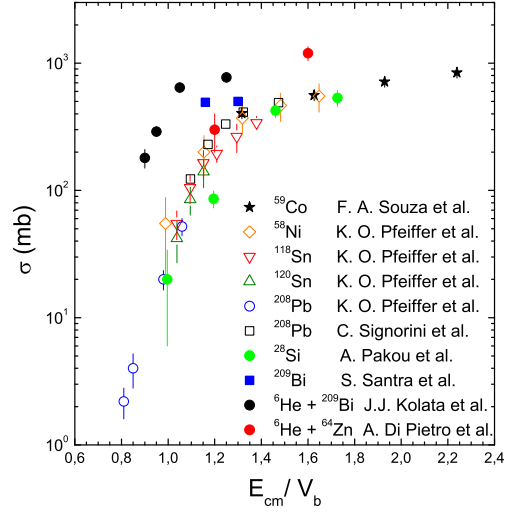
Figure 2. (Color online) Total α-production cross sections for a number of systems involving ^{6}Li [15,16,17,18,19,20] and ^{6}He projectiles [4,21]. In particular, the data corresponding to the ^{6}Li+^{59}Co reaction, and plotted as full stars, have been obtained from Ref. [19]).

Several experiments involving stable, weakly-bound projectiles such as ^{6}Li, ^{7}Li and ^{9}Be on medium-mass targets have been undertaken in the recent past [1,12,17,18,19]. The main results are summarized in Figs. 1 and 2 along with selected experimental data obtained for ^{6}He, ^{8}Li, ^{8}B, ^{7,11}Be and ^{17}F exotic beams [2,3,4,9,10,11,24,25]. Of particular interest are the very large total reaction cross sections observed in Fig. 1 for the "halo" systems ^{6}He+^{64}Zn [4], ^{8}B+^{58}Ni [2] and ^{6}He+^{209}Bi [21] (upper red curve) in comparison with weakly-bound "normal" systems (lower red curve). Please note that the data points for ^{6}He+^{208}Pb [22] and ^{6}He+^{197}Au [23] total reaction cross sections, being compatible with those measured for ^{6}He+^{209}Bi [21], were not plotted in Fig. 1.

The two classes of projectile yield two distinct curves for the "reduced" cross sections as a function of the "reduced" energy (as defined in Refs.[2,12,14]). Both the "halo" systems (a weakly bound proton is still confined by the Coulomb barrier and thus gives

less than a halo) and the stable weakly-bound systems have cross sections which lie well above the systematic behavior defined by the very tightly-bound systems $^{16}O+^{64}Zn$ [12] illustrated by the blue curve of Fig. 1. The $^{16}O+^{58}Ni$ [26] as well as the $^{17}F+^{58}Ni$ [24] total reaction cross sections (not shown in Fig. 1) belong also to the blue curve. The fact that the weakly-bound ^{17}F and the tightly-bound ^{16}O nuclei [24] show the same trend may indicate that nuclear structure effects still play a prominent role in the reaction dynamics.
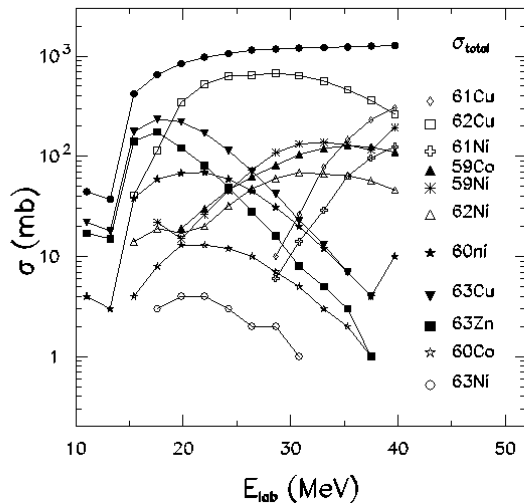

Figure 3. CASCADE (CACARIZO [38]) predictions for excitation functions of evaporation residues produced in $^6Li+^{59}Co$ complete fusion reactions. The corresponding experimental data were given in Fig. 1 of Ref. [17].
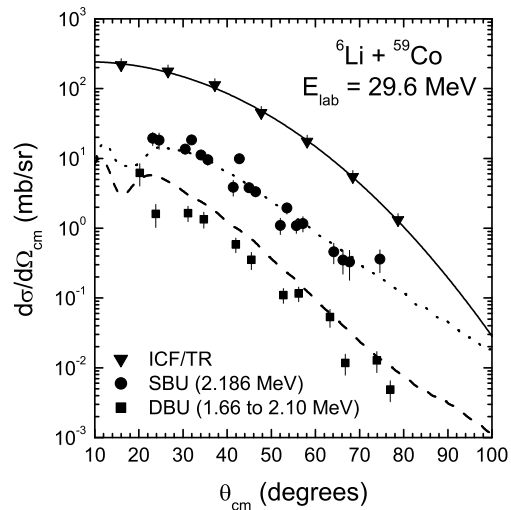
Figure 4. Experimental (Full triangles circles and rectangles) and theoretical (solid, dashed and dotted curves) angular distributions for the ICF/TR, SBU and DBU processes (see text).

Similarly, total α production is also found to be more intense for $^6He+^{64}Zn$ [4] and $^6He+^{209}Bi$ [21] when compared, in Fig. 2, to the universal function determined in Ref. [19] for reactions induced by ^6Li projectiles. It is interesting to note that reactions induced by ^7Li projectiles [27] obey the same systematic trend, giving further support to the present comparisons. Since there still exist contradictory results for beryllium isotopes, it will be of great interest to see how the recent Rex-Isolde measurements for $^{11}Be+^{64}Zn$ [25] (for

example, preliminary total reaction cross sections are found to be at least twice those for ^{9}Be+^{64}Zn [12]) will follow the systematics of both Fig. 1 and Fig. 2. For instance, Kolata and collaborators [28] have argued that the total reaction cross section measured earlier for ^{9}Be+^{209}Bi [29] was very much enhanced compared with that for ^{10}Be+^{208}Pb [28] at sub-barrier energies, due to the weakly-bound nature of the ^{9}Be projectile. However, and despite the ^{11}Be halo structure. up to now no significant difference has been observed between ^{9,11}Be+^{209}Bi [29,30] and ^{10}Be+^{208}Pb [28]. It may appear important to perform as soon as possible new experiments of this type, but with high-quality Beryllium beams that have recently become available at Rex-Isolde.

A comprehensive study of ^{6}Li+^{59}Co [13,17,19,31,32,33,34,35] (considered as a benchmark reaction) is still in progress. Results on total reaction cross sections extracted from the optical model (OM) analysis [36] of the elastic scattering (using the São Paulo Potential [36]) are shown in Fig. 1 as magenta triangles, and the corresponding total α production cross sections are indicated by full stars in Fig. 2. The comparison with Continuum-Discretized Coupled-Channel (CDCC) calculations [13,31] indicates only a small enhancement of total fusion for the more weakly-bound ^{6}Li below the Coulomb barrier, with similar cross sections for both ^{6,7}Li+^{59}Co reactions at and above the barrier. Although rather low breakup cross sections were measured for ^{6,7}Li+^{59}Co, even at incident energies higher than the Coulomb barrier [13,31], the coupling to the breakup channel is extremely important for the CDCC analysis [13,37] of the elastic scattering angular distributions [36].

3. DISCUSSION

Fig. 3 displays ^{6}Li+^{59}Co excitation functions for fusion-evaporation residue (ER) channels as predicted by CACARIZO, the Monte Carlo version of CASCADE [38]. This uses rather well established input parameters for the medium-mass region A $\approx$ 60. The unexpected disagreement with the experimental data for almost all of the dozen or so ER channels [17] was interpreted as a signature of the occurence of intense incomplete-fusion (ICF) components. A careful investigation was later undertaken in Ref. [39] for the three strongest ER channels for ^{6}Li+^{59}Co, using two other well-known statistical-model codes (PACE2 and EMPIRE-II), and similar conclusions on the role of ICF were proposed. We would like to point out that the statistical-model simulation with CASCADE, presented in the present work, is in fairly good agreement (within 30%) with both PACE2 and EMPIRE-II calculations [39]. Although the ICF hypothesis was invoked, one should remain rather cautious when using evaporation codes for fusion induced by weakly-bound projectiles or halo projectiles such as ^{6}He [3,4]. In the latter case [3,4], the importance of the role of transfer channels rather than ICF has been proposed. However, for exotic nuclei populated in this kind of fusion reaction, there is, unfortunately, a real lack of information on both OM parameters (transmission coefficients) and level densities (see for instance Ref. [40,41]) which are among the key input parameters of evaporation codes.

A detailed study of the breakup process in the ^{6}Li+^{59}Co reaction with particle techniques allowed us to discuss the interplay of fusion (CF and ICF) and breakup processes [13]. Coincidence data registered at E$_{lab}$ = 29.6 MeV, compared with three-body kinematics calculations [19,34,35], reveal how to disentangle the contributions from

breakup, ICF and/or transfer-re-emission processes (TR). A very preliminary estimate of the total experimental ICF cross section would give approximately 150 mb. This value appears to be consistent with a calculation performed using the model of Diaz-Torres [42].

Fig. 4 depicts the experimental angular distributions for both the sequential breakup (SBU) and ICF/TR processes analysed in Ref. [19], as well as for the direct breakup (DBU) components. For the case of ICF/TR, we used the differential cross sections extracted from inclusive data [19]. The solid and dotted lines were extracted from Ref. [19] and correspond to the ICF/TR Gaussian fit and the SBU CDCC calculation [13], respectively. The dashed line represents the DBU CDCC results [13] for the ^{6}Li excitation energy range from $E^* = 1.48$ MeV (breakup threshold) to $E^* = 2.10$ MeV in the continuum.
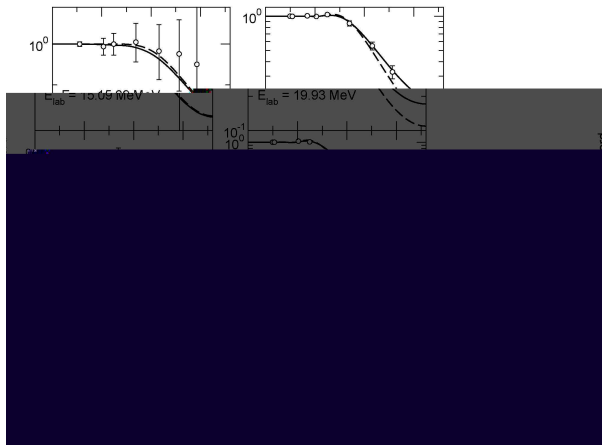

Figure 5. ^{7}Be+^{58}Ni elastic scattering measurements (experimental data are from [2]). Solid and dashed curves are CDCC calculations [37] with respectively full-coupling and without coupling as explained in the text.
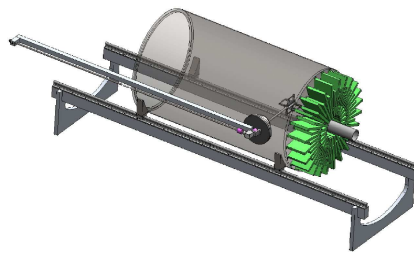

Figure 6. (color online) R&D design of the MSU/NSCL active-target time-projection chamber to be installed within the solenoid: view of the chamber with a removable target wheel [44].

As far as exotic "halo" projectiles are concerned we have initiated a systematic study of the ^{8}B and ^{7}Be induced reactions data [2] (partly displayed in Fig. 1) with an improved CDCC method [13,37]. Some of the preliminary results on the angular distributions are displayed in Fig. 5 for the ^{7}Be+^{58}Ni elastic scattering. As compared to ^{7}Be+^{58}Ni (similar to ^{6,7}Li+^{58,60}Ni) our CDCC analysis of the ^{8}B+^{58}Ni reaction (not shown in the present paper since it is in full agreement with the work of Lubian et al. [43]) while exhibiting a large breakup cross section (consistent with the experimental systematics [14]) is rather surprising as regards the consequent weak-coupling effect found to be particularly small in the near-barrier elastic scattering measurements [2]. A more detailed discussion with comparisons of coupling effects for near-barrier ^{6}Li, ^{7}Be and ^{8}B elastic scattering angular distributions is proposed in Ref. [37].

4. SUMMARY, CONCLUSIONS AND OUTLOOK

A systematic overview of the competition of various reaction mechanisms induced by either stable, weakly-bound or exotic, halo nuclei is proposed in Fig. 1 and Fig. 2, where a large number of recent experimental results are compiled and briefly presented. The correctness of the statistical-model codes is critically discussed for reactions induced by RIB projectiles for which essential input parameters such as level densities and OM transmission coefficients are less well known. From a detailed investigation of the ^{6}Li+^{59}Co reaction, it can be concluded that a clear separation of the different reaction mechanisms remains one of the main challenges in the study of fusion reactions induced by stable, weakly-bound and exotic, halo projectiles with medium-mass targets in the vicinity of the Coulomb barrier and below. For halo systems a full understanding of the reaction dynamics involving couplings to the breakup and nucleon-transfer channels will need high-intensity radioactive ion beams (presently available at SPIRAL/GANIL [3], DRIBs/Dubna [7], Rex-Isolde [25], MSU/Notre-Dame [2,44], RIBRAS/São Paulo [11], RIPS/RIKEN [30] ...) and precise measurements of elastic scattering, fusion and yields for breakup itself. A proposal [44] to study reactions such as ^{8}B+^{40}Ar and ^{11}Be+^{40}Ar, using an active-target time-projection chamber (AT-TPC), is underway at MSU/NSCL. The AT-TPC is a dual functionality device containing both traditional active-target and time-projection chamber capabilities. The detector consists of a large gas-filled chamber installed in an external magnetic field (solenoid) as shown in Fig. 6.

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